protons of ~200 keV. Only the ground state of ^{23}Al is likely to be bound, since the first excited state of the analog nucleus ^{23}Ne lies at 1.02 MeV.[7]

Both of these nuclei complete isobaric quartets[8,9]; their masses have already been predicted by the isobaric multiplet mass equation (IMME), as discussed in Ref. 1, and thus permit yet another check of its validity. Mass predictions for these nuclei from the IMME,[1] from a systematic study of Coulomb energies in the $1d_{5/2}$ shell,[9] and from the Kelson-Garvey nuclidic mass relationship[10] are given in Table I. Good agreement is to be seen among the various theoretical predictions and between them and experiment for both ^{19}Na and ^{23}Al.

We would like to thank Dr. Jurgen Radeloff for developing the fast preamplifier used in these experiments, Dr. Francesco Resmini and Dr. David Clark for their efforts in preparing beams with suitable phase widths, Barbara Cerny for writing the off-line analysis program, and John Bowen and the cyclotron crew for maintaining the beam throughout a long, arduous run.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]J. Cerny, Ann. Rev. Nucl. Sci. 18, 27 (1968).

[2]R. L. McGrath, J. Cerny, and E. Norbeck, Phys. Rev. Letters 19, 1442 (1967).

[3]G. W. Butler, J. Cerny, S. W. Cosper, and R. L. McGrath, Phys. Rev. 166, 1096 (1968).

[4]J. L. Wiza and R. Middleton, Phys. Rev. 143, 676 (1966).

[5]Very tentative evidence for the reaction ^{16}O(p, ^{6}He)^{11}N on oxygen target impurities was noted; however, this transition could not interfere with the ground-state measurements.

[6]The ^{22}Mg mass is taken to be -377 ± 16 keV as a weighted average of the values reported in J. Cerny, S. W. Cosper, G. W. Butler, R. H. Pehl, F. S. Goulding, D. A. Landis, and C. Détraz, Phys. Rev. Letters 16, 469 (1966); P. H. Barker, N. Drysdale, and W. R. Phillips, Proc. Phys. Soc. (London) 91, 587 (1967); A. B. McDonald and E. G. Adelberger, Bull. Am. Phys. Soc. 12, 1145 (1967); J. M. Adams, A. Adams, and J. M. Calvert, J. Phys. A: Phys. Soc. (London) Proc. 1, 549 (1968).

[7]A. J. Howard, J. P. Allen, D. A. Bromley, J. W. Olness, and E. K. Warburton, Phys. Rev. 154, 1067 (1967).

[8]In fact, as is discussed in Refs. 1 and 9, the mass 19 isobaric multiplet for which three members are known comprises the first excited $T=\frac{3}{2}$ states ($J^\pi=\frac{3}{2}^+$) in the $T_Z=\frac{3}{2}$, $\frac{1}{2}$, and $-\frac{1}{2}$ nuclei.

[9]J. C. Hardy, H. Brunnader, J. Cerny, and J. Jänecke, to be published.

[10]I. Kelson and G. T. Garvey, Phys. Letters 23, 689 (1966).

THE DECAY $\Sigma^\pm \to \Lambda e^\pm \nu$†

C. Baltay,* P. Franzini, R. Newman, H. Norton, and N. Yeh
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

J. Cole, J. Lee-Franzini, R. Loveless, and J. McFadyen
State University of New York, Stony Brook, New York 11790,
and Brookhaven National Laboratory, Upton, New York 11973

(Received 20 February 1969)

We have observed 46 examples of the decay $\Sigma^- \to \Lambda e^- \nu$ and six of the decay $\Sigma^+ \to \Lambda e^+ \nu$. The branching ratios are, respectively, $(0.52 \pm 0.09) \times 10^{-4}$ and $(0.16 \pm 0.07) \times 10^{-4}$. A study of the internal variables distribution yields $G_V/G_A = -0.7 \pm 0.4$ for the combined sample of $\Sigma^\pm \to \Lambda e^\pm \nu$.

The decays $\Sigma^\pm \to \Lambda e^\pm \nu$ offer one of the rare instances in which it is possible to measure a matrix element of the strangeness-conserving weak current between baryon states. Lorentz invariance and the absence of second-class currents imply that the matrix element in question may be written as[1]

$$\langle \Lambda | J_\mu^{\Delta S=0} | \Sigma \rangle = \bar{u}_\Lambda \{ G_V \gamma_\mu + (G_{\rm wk}/M) \sigma_{\mu\nu} q_\nu + G_A \gamma_\mu \gamma_5 + (G_{\rm ps}/M) q_\mu \gamma_5 \} u_\Sigma. \tag{1}$$

The complete amplitude for $\Sigma^- \to \Lambda e^- \nu$ decay is given by

$$\mathfrak{M} = \langle \Lambda | J_\mu | \Sigma \rangle \bar{u}_e \gamma_\mu (1+\gamma_5) u_\nu. \tag{2}$$

Because of the small Q value in this decay the effects of the weak magnetism and induced pseudoscalar terms are undetectable in this experiment and are therefore neglected in our analysis. We will further ignore the momentum dependence of G_V and G_A and refer to them as the vector and axial-vector coupling constants, respectively.

Various hypotheses have been proposed concerning the properties of J_μ. The most interesting one, the so-called hypothesis of conserved vector current,[2] relates the vector part of the weak current $J_\mu{}^{\Delta S=0}$ to the isovector part of the electromagnetic current. A consequence of the hypothesis of conserved vector current for this decay is that $G_V=0$ for $\Sigma\rightarrow\Lambda e\nu$ decays.[3]

For a decay amplitude of the form given above, the absolute value of the constants G_V and G_A can be determined by studying the correlations between the coordinates in momentum space of the decay products. In addition, the Λ^0 polarization is sensitive to the relative amount of vector and axial-vector coupling and to their relative sign. The Λ^0 polarization can be inferred from a study of the Λ^0 decay angular correlation. The complete distribution function for both the Σ decay products and the Λ^0 decay products can be directly obtained by writing the amplitude for the chain of decays as

$$A(\Sigma\rightarrow\Lambda,\ \Lambda\rightarrow\pi p)$$
$$=\bar{u}_p(1+\chi\gamma_5)u_\Lambda\bar{u}_\Lambda\gamma_\mu(g_V+g_A\gamma_5)u_\Sigma(e\nu)_\mu. \quad (3)$$

In this expression, χ describes parity violation in Λ^0 decay and is related to the asymmetry parameter α by $\alpha\, 2P\chi/[E(1+\chi^2)+m(1-\chi^2)]$, where E, P, and m are the proton energy, momentum, and mass, respectively, in the Λ^0center of mass system, and α is the proton helicity in Λ^0 decay. Summing coherently over the Λ^0 spin orientations, one obtains

$$A(\Sigma\rightarrow\Lambda,\Lambda\rightarrow\pi p)=\bar{u}_p(1+\chi\gamma_5)\left(\frac{-i\not{P}_\Lambda+m_\Lambda}{2m_\Lambda}\right)$$
$$\times\gamma_\mu(G_V+G_A\gamma_5)u_\Sigma(e\nu)_\mu. \quad (4)$$

From this amplitude, the complete distribution function is obtained in the standard way:

$$f(P_\nu,P_e,P_\Lambda,P_p)=\sum_{\Sigma,\,\nu,\,e,\,p\text{ spin}}|A|^2. \quad (5)$$

Examples of the decays $\Sigma^\pm\rightarrow\Lambda e^\pm\nu$ were obtained from the study of a large exposure of the 30-in. liquid-hydrogen bubble chamber to stopping K^- from the low-energy separated beam at the Brookhaven National Laboratory alternating-gradient synchrotron. Approximately 2×10^6 Σ^- and 10^6 Σ^+ were produced and decayed inside the chamber.

The entire exposure was double scanned and about one-half was rescanned for a third time. The efficiency of the entire double scan is estimated to be $95\,\%\pm5\,\%$ for events which later satisfied all acceptance criteria.

The decays of interest are extremely rare (less than $1{:}10^4$ ordinary decays). However, the decay of a Σ into an electron of less than 80 MeV accompanied by the nearby decay of the Λ^0 into a π^- and a proton is quite unique and can be simulated only by even rarer processes due to either the Σ^- capture at rest and/or random association with Λ^0 decay, all this accompanied by the rare internal conversion of a γ ray into a very asymmetric Dalitz pair.

There were 80 candidates retained for measurements after inspection by physicists of all events found in scanning.

The chain of production and decays

$$K^-p(\text{at rest})\rightarrow\Sigma^\mp\pi^\pm,$$
$$\Sigma^\mp\rightarrow\Lambda^0e^\mp\nu,$$
$$\Lambda^0\rightarrow\pi^-p \quad (6)$$

is seven times overconstrained. It was thus possible to obtain a sample essentially free of background by requiring a fit to the seven constraints hypothesis above. All events which failed after remeasurement and a second attempt at fitting were examined by physicists and found not to be examples of the decay of interest.

Events accepted satisfied the criteria $\chi^2<25$, as well as the condition that all tracks had bubble densities consistent with the measured momenta and assigned masses. We obtain 46 $\Sigma^-\rightarrow\Lambda^0e^-\nu$ and six $\Sigma^+\rightarrow\Lambda^0e^+\nu$ events.

The final sample is believed to be representative of the complete decay distribution certainly to a better accuracy than the statistical limitations of our sample. This is mostly because observations are made in the laboratory where little or no memory is left of the crucial center-of-mass parameters.

The best value for the ratio G_V/G_A can be obtained by calculating the likelihood of our combined sample of Σ^- and Σ^+ as a function of G_V/G_A by using the distribution function indicated in Eq. (5).[4] The result of such a calculation is shown in Fig. 1. The best value for the ratio is $G_V/G_A = -0.7 \pm 0.4$ using a value of $\alpha = +0.65$.[5] The sign convention used here corresponds to the ratio G_V/G_A being positive for neutron β decay.[6]

The internal consistency of the data can be checked by comparing experimental distributions for the Σ^- events with predictions derived using the experimental result $G_V/G_A = -0.7$. Since the number of events is so few, we prefer to quote values of G_V/G_A assumed real obtained using only (a) the electron neutrino angular correlation, (b) the Λ^0 polarization in the $\vec{\alpha}$ direction[7] (essentially the Λ^0 helicity), and (c) the Λ^0 polarization in the $\vec{\beta}$ direction[7] (essentially the Λ^0 polarization in the decay plane perpendicular to the line of flight). We obtained, respectively, (a) $|G_V/G_A| = 0.5^{+0.6}_{-0.5}$, (b) $\vec{S}_\Lambda \cdot \vec{\alpha} = 0.3 \pm 0.4$, $G_V/G_A = -0.4^{+0.5}_{-0.7}$, and (c) $\vec{S}_\Lambda \cdot \vec{\beta} = +0.4 \pm 0.4$, $|G_V/G_A| = 1.7^{+4.9}_{-1.3}$, where $\vec{S}_\Lambda$ is the Λ polarization. Both the values and the statistical errors were obtained using a moments analysis. For reference, we show the Λ kinetic-energy distribution, Fig. 2, with the expected distributions.

In addition, the third component of the Λ^0 polarization, along the $\vec{\gamma}$ direction,[7] should be zero under the assumption of time-reversal invariance. We obtain $\vec{S}_\Lambda \cdot \vec{\gamma} = -0.2 \pm 0.3$ corresponding to a completely imaginary G_V/G_A of $-0.4^{+0.8}_{-1.2}$.

A smaller sample of events, which satisfy a more rigid set of good visibility criteria, has been used to obtain the partial decay rates. The criteria are as follows: Λ, p, and $e^\pm$ dip $\leq 70°$, Λ and p projected lengths ≥ 1 mm, Σ length ≥ 1 mm, and ≤ 10 mm for Σ^-, ≤ 11.5 mm for Σ^+. A Monte Carlo calculation indicates that 44% of the $\Sigma^- \to \Lambda e^- \nu$ and 49% of the $\Sigma^+ \to \Lambda e^+ \nu$ events would survive these criteria. We obtain

$$\Gamma(\Sigma^- \to \Lambda e^- \nu)/\Gamma(\Sigma^- \to \text{all}) = (\text{no. observed events})(\text{corrections})/(\text{no. produced } \Sigma\text{'s})$$

$$= 31 \times 3.59/2.13 \times 10^6 = (0.52 \pm 0.09) \times 10^{-4}.$$

Similarly,[8]

$$\Gamma(\Sigma^+ \to \Lambda e^+ \nu)/\Gamma(\Sigma^+ \to \text{all}) = 5 \times 3.21/0.99 \times 10^6 = (0.16 \pm 0.07) \times 10^{-4}.$$

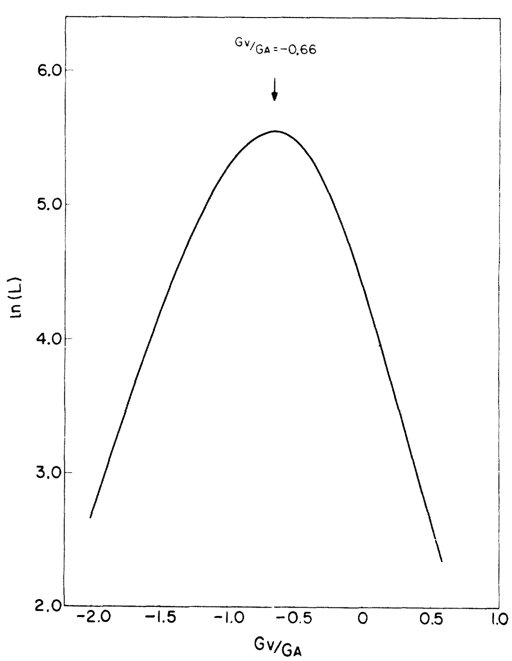

FIG. 1. Log of the likelihood as a function of the G_V/G_A ratio obtained in the maximum-likelihood fit using 46 $\Sigma^- \to \Lambda e^- \nu$ and six $\Sigma^+ \to \Lambda e^+ \nu$ decays.

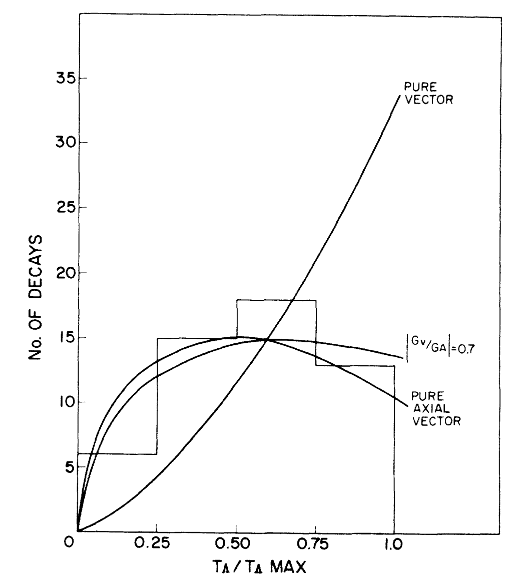

FIG. 2. Distribution in the lambda kinetic energy T_Λ in the $\Sigma^\pm$ center-of-mass frame for 46 $\Sigma^- \to \Lambda e^- \nu$ and six $\Sigma^+ \to \Lambda e^+ \nu$ decays. The superimposed curves are the theoretical distributions for various values of the ratio G_V/G_A.

From these two results and a knowledge of the Σ^+ and Σ^- lifetimes, we also obtain the ratio of the two partial widths:

$$R = \Gamma(\Sigma^- \to \Lambda e^- \nu)/\Gamma(\Sigma^+ \to \Lambda e^+ \nu) = 1.6 \pm 0.7$$

to be compared with the value $R = 1.64$ obtained under the assumption that the strangeness-conserving weak current transforms as an isovector.

We would like to thank the operating crews of the alternating-gradient synchrotron and the 30-in. bubble chamber at Brookhaven National Laboratory for their help during the experimental runs. We are also very grateful to the scanning and measuring staffs at Columbia University and Stony Brook for their untiring efforts.

†Research supported in part by the U. S. Atomic Energy Commission.

*Sloan Foundation Fellow: 1967-1969.

[1]See, for example, M. Cabibbo and P. Franzini, Phys. Letters 3, 217 (1963); W. Alles, Nuovo Cimento 26, 1429 (1962).

[2]R. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958); R. Marshak and E. Sudarshan, Phys. Rev. 109, 1860 (1958).

[3]N. Cabibbo and R. Gatto, Nuovo Cimento 15, 159 (1960).

[4]The Σ^+ distribution function is obtained by interchanging the lepton variables in the expression for Σ^- decay.

[5]If we leave α free in the likelihood calculation, we obtain $\alpha = +0.8 \pm 0.3$.

[6]This result should be compared with previous measurements as summarized by J. Cronin, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 289. A complete set of references to previous measurements is given in this article.

[7]$\vec{\alpha} = (\hat{e} + \hat{\nu})/|\hat{e} + \hat{\nu}|$, $\vec{\beta} = (\hat{e} - \hat{\nu})/|(\hat{e} - \hat{\nu})|$, $\vec{\gamma} = \hat{e} \times \hat{\nu}/|\hat{e} \times \hat{\nu}|$, as defined in W. Alles, Nuovo Cimento 26, 1429 (1962).

[8]For normalization, we counted the number of Σ^- produced and computed the number of Σ^+ produced using a production rate of $\Sigma^+/\Sigma^- = 0.465$, as given by W. E. Humphrey and R. R. Ross, Phys. Rev. 127, 1305 (1962).

ENERGY DEPENDENCE OF THE 180° $\pi^- p$ CHARGE-EXCHANGE CROSS SECTION

V. Kistiakowsky and R. K. Yamamoto
Massachusetts Instutute of Technology,* Cambridge, Massachusetts 02139

and

R. D. Klem, P. Marcato, I. A. Pless,† and I. Spirn
Argonne National Laboratory, Argonne, Illinois 60439

and

E. F. Anelli, C. N. De Marzo, and A. Romano
Istituto di Fisica dell'Università di Bari, and Istituto Nazionale di Fisica Nucleare, Sottosezione di Bari, Italy

and

D. G. Crabb, A. C. Meyers, III, and J. R. O'Fallon
St. Louis University, St. Louis, Missouri 61303
(Received 23 January 1969)

We present preliminary data which demonstrate that the $\pi^- p$ charge-exchange differential cross section at 180° in the momentum region between 1.8 and 5.0 BeV/c is quite similar in shape to the elastic $\pi^\pm$ differential cross sections at 180°.

Data reviewed by Bellettini[1] indicated that the energy dependence of the differential cross section at 180° for $\pi^- p$ charge exchange ($\pi^- p \to \pi^0 n$) differed in shape from the differential cross sections at 180° for π^+ and π^- elastic scattering ($\pi^\pm p \to \pi^\pm p$).[1] We present preliminary data here which demonstrate that the differential cross section at 180° for charge exchange is quite similar to those for elastic scattering.

The experiment was performed in the 17° negative pion beam at Argonne National Laboratory. The experimental configuration is shown in Fig. 1. The momentum slit was set to transport a $\Delta p/p$ of 0.75%. A series of counters B_1, $\check{C}$, B_2, B_3, and B_4 define the incident pion beam. $\check{C}$ is a Čerenkov counter which eliminates K^- and p^- particles and also is used to measure the electron and muon contamination. B_1, B_2, B_3, and B_4